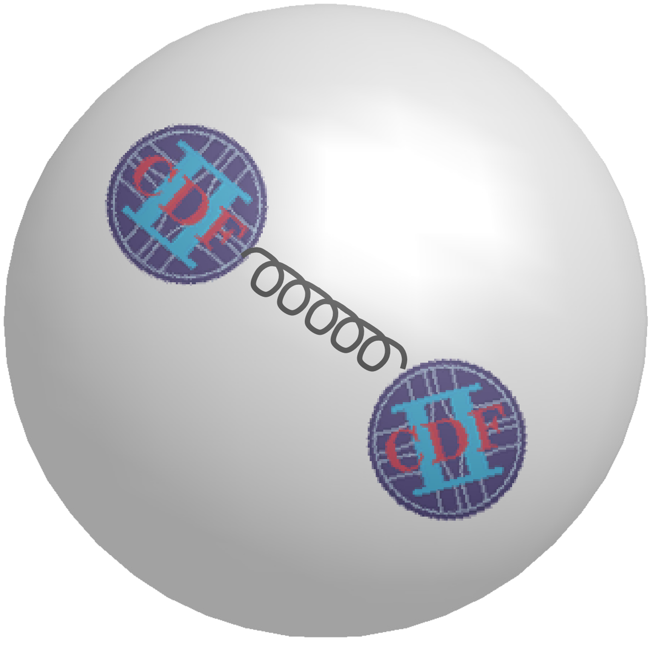
Quarkonium Spectroscopy and Decay results from CDF



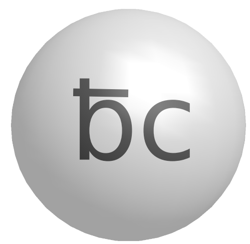
Thomas Kuhr
KIT

Quarkonium Workshop

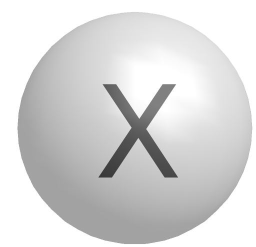
December 3, 2008

Outline

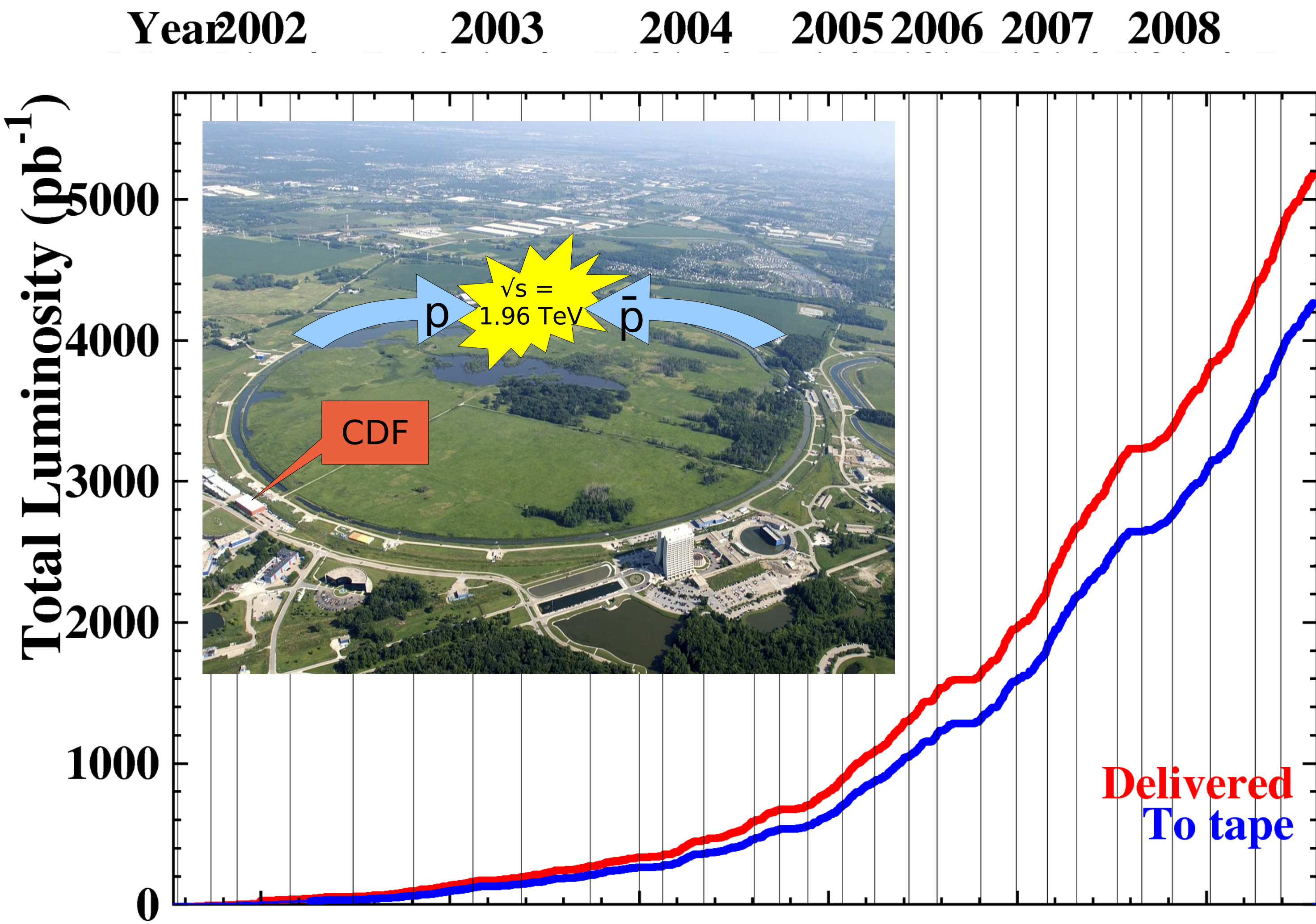
- Tevatron and CDF
- B_c
  - → Mass
  - → Lifetime



- X(3872)
  - → Mass splitting and mass



Tevatron

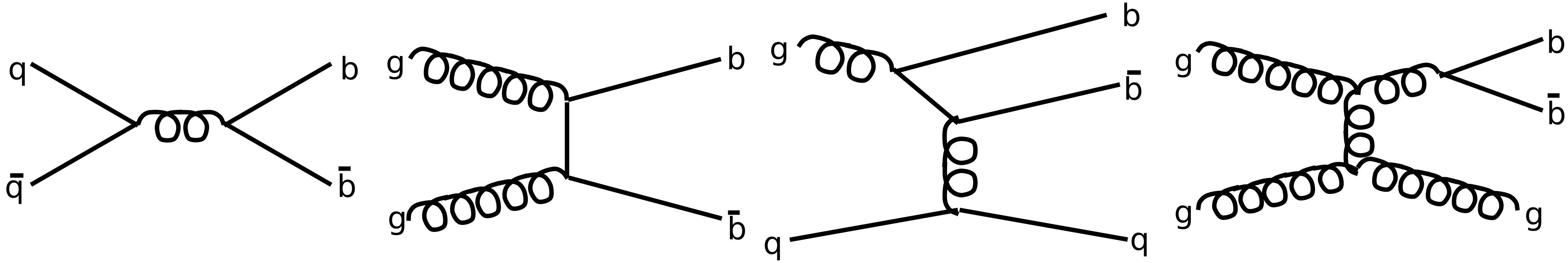


4.3 fb^{-1} on tape

B_c mass, X(3872) mass

B_c lifetime

Heavy hadron production at the Tevatron

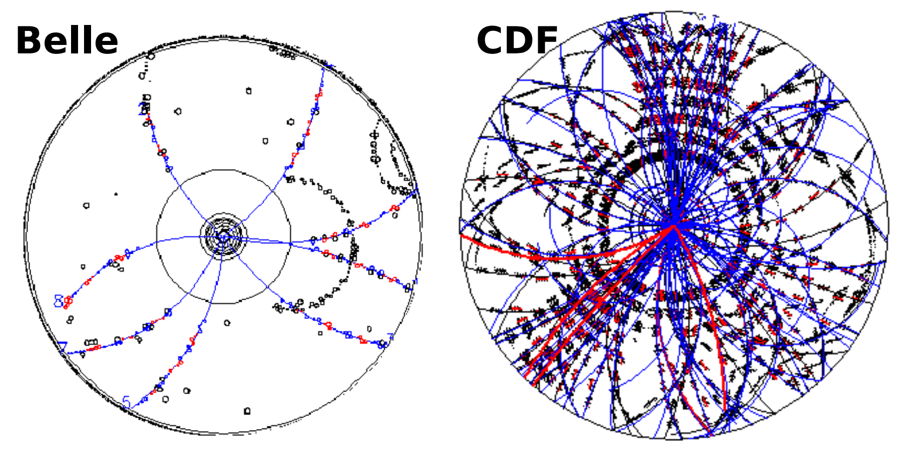


- ➔ Huge $b\bar{b}$ and $c\bar{c}$ cross section
- ➔ Production of all heavy hadron species in fragmentation

but

- ✗ inelastic cross section ~10^3 times larger than $\sigma(b\bar{b})$
  $\rightarrow$ Trigger: muon pairs, displaced tracks

- ✗ Background tracks from fragmentation
  $\rightarrow$ High combinatorial background



CDF Detector

Muon Chambers

- Muon ID

Central Drift Chamber

- Momentum, mass
- PID

Silicon vertex tracker

- Lifetime

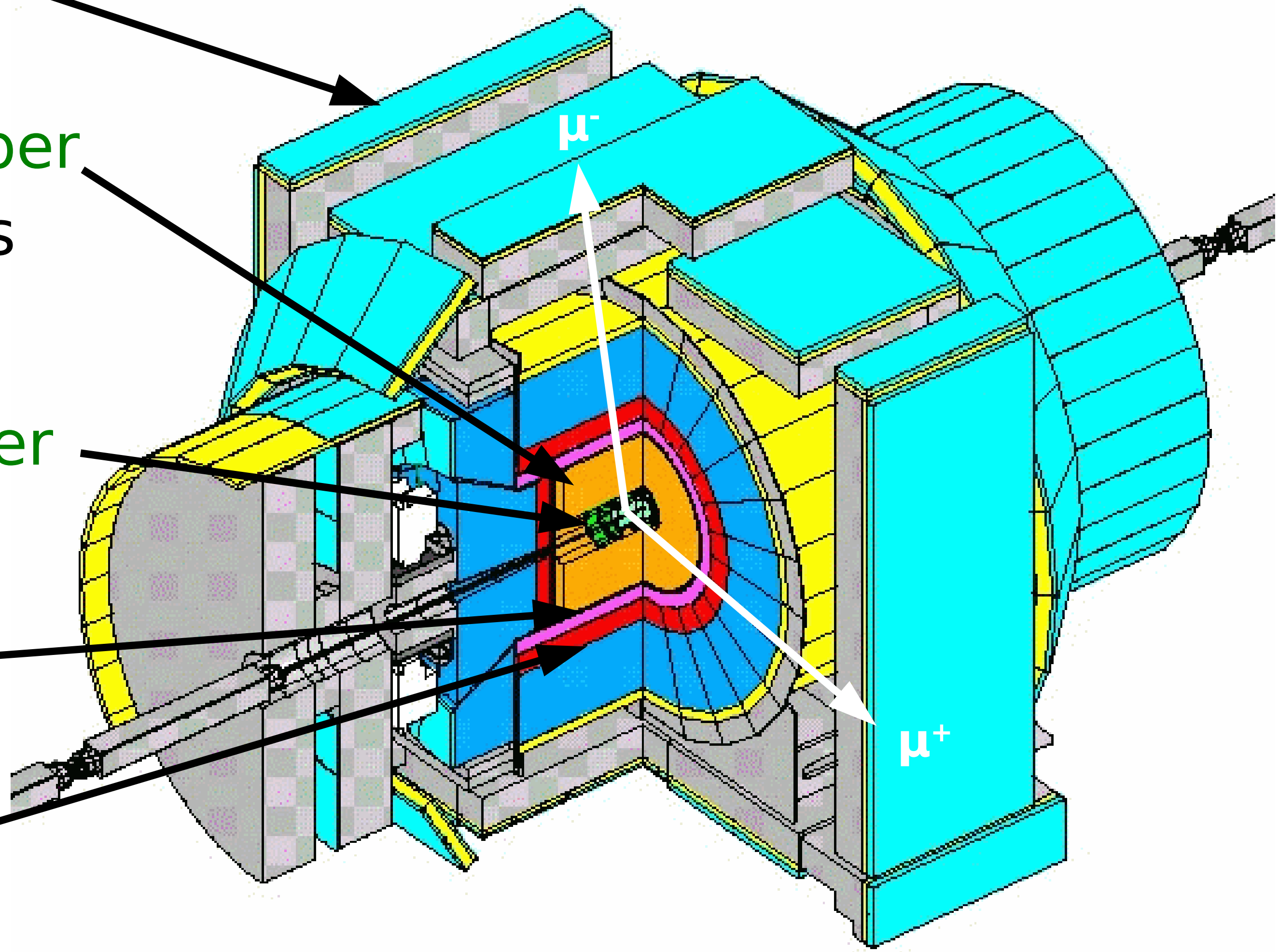
Time of flight

- PID

Calorimeters

- Electron ID

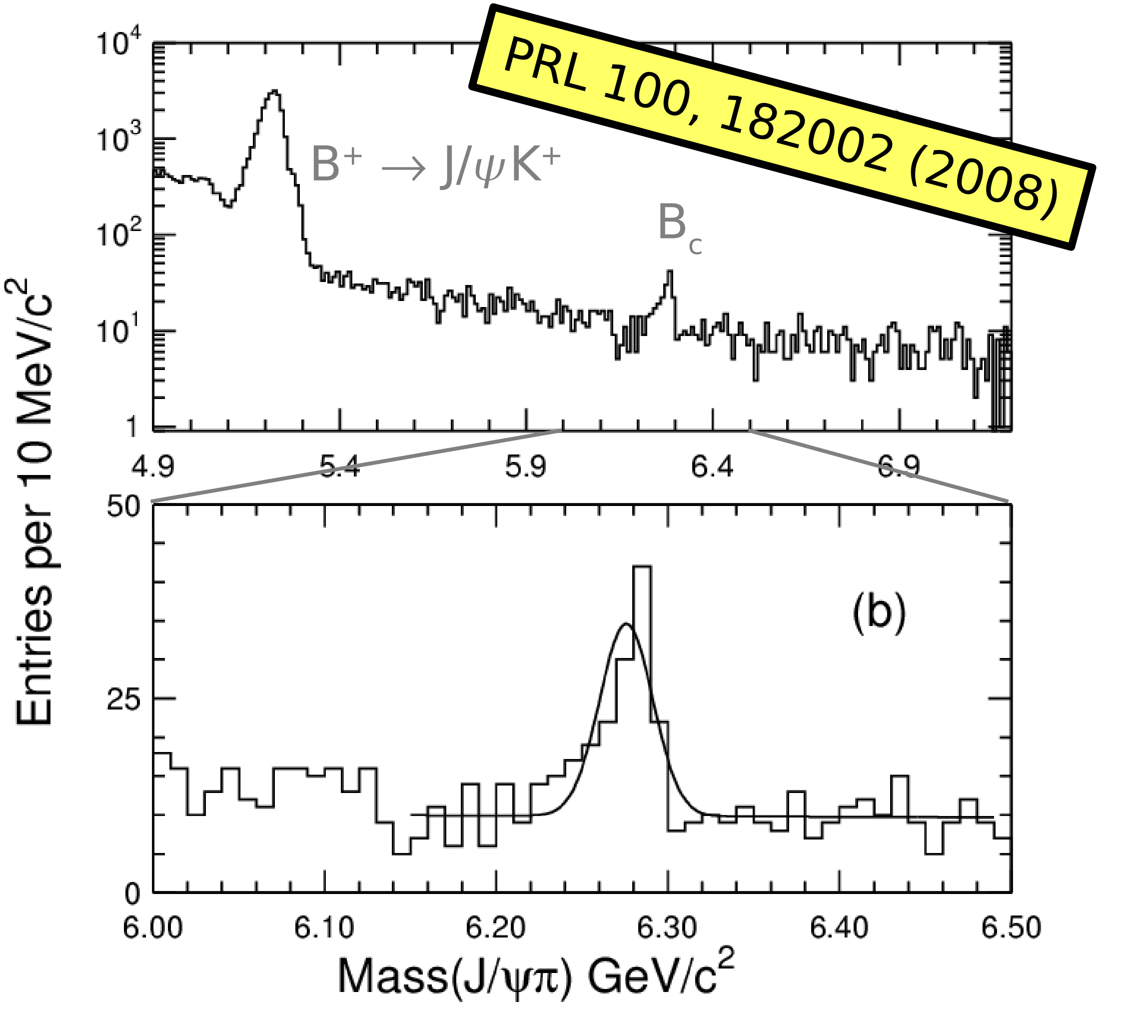
$J/\psi \rightarrow \mu^+ \mu^-$ Trigger



B_c Mass

- Only meson with two different heavy quarks
  - ➔ Test of QCD models and calculations

- Mass measurement in $J/\psi\pi$ decay channel
  - ➔ *Full reconstruction*
- Update to 2.4 fb^{-1}
- Significance > 8σ

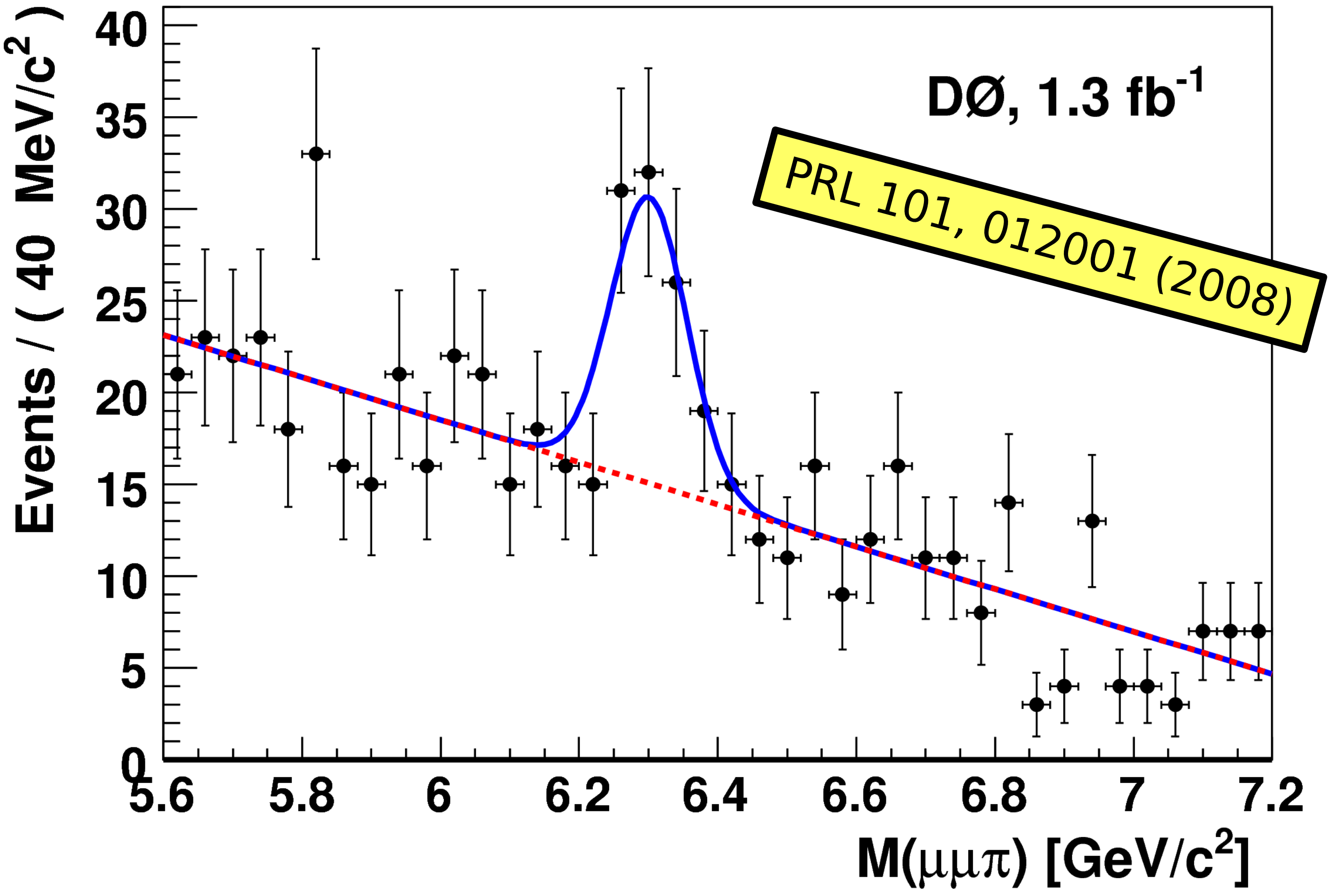


➢ $M(B_c) = 6275.6 \pm 2.9$ (stat) ± 2.5 (syst) MeV/c^2

B_c Mass (DØ)

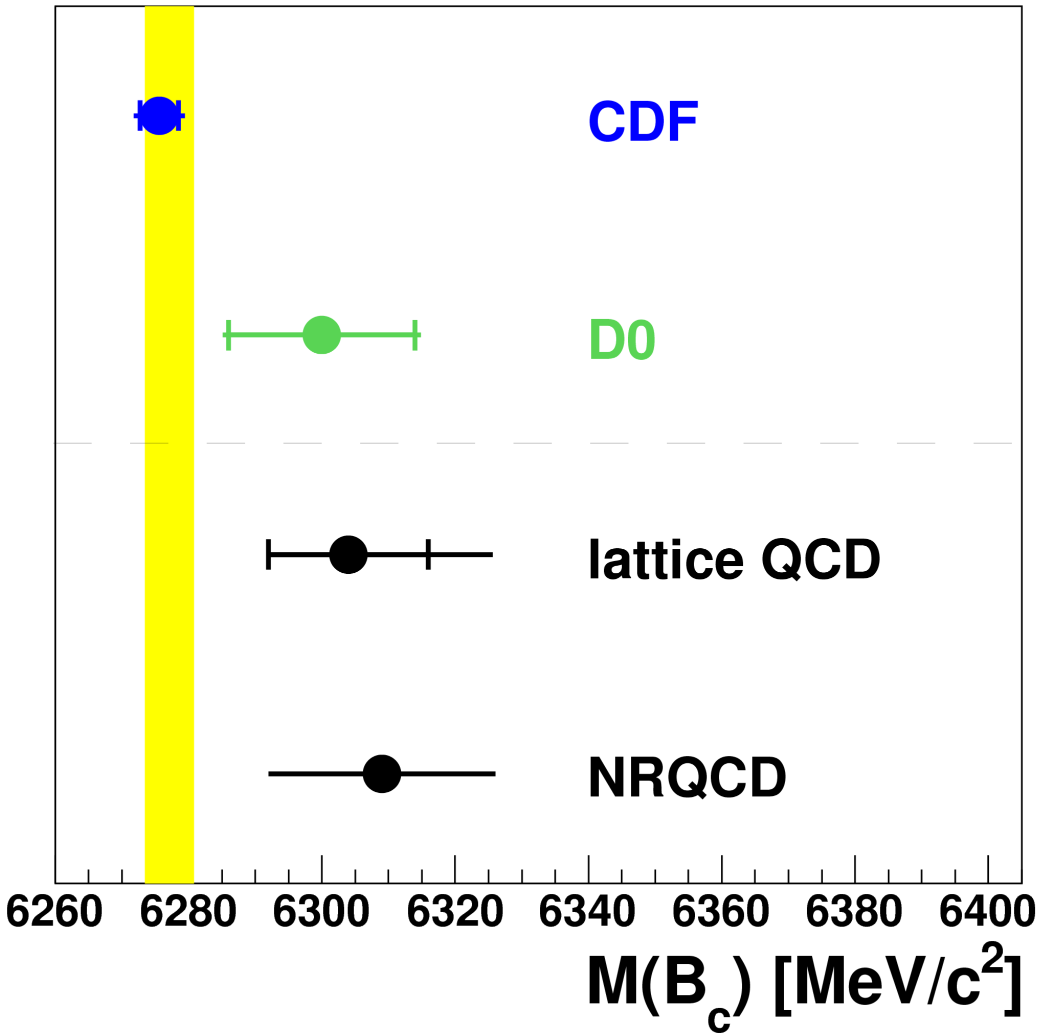
b̄c

- Full reconstruction in $J/\psi\pi$ mode
- Cuts optimized on $B^+ \to J/\psi K^+$ data and B_c MC
- 1.3 fb^{-1}
- Significance $> 5\sigma$



- $M(B_c) = 6300 \pm 14\ (stat) \pm 5\ (syst)\ MeV/c^2$

B_c Mass Results

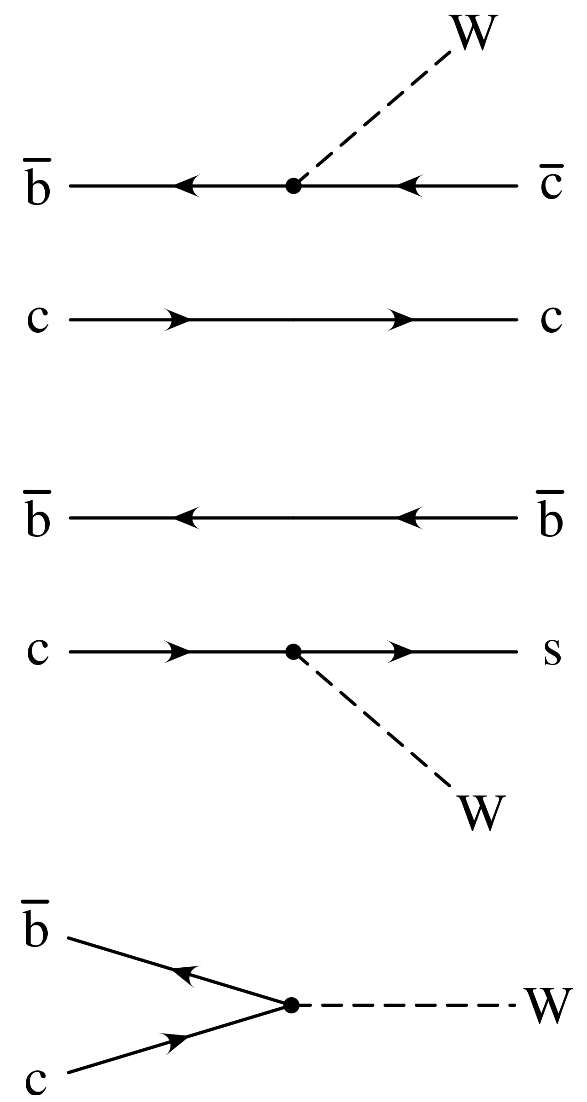


- ➔ CDF and D0 results agree within 1.6σ
- Lattice QCD [PRL 94, 72001 (2005)] and NRQCD [PRD 65, 034001 (2002)]:
  - $\sim 2\sigma$ higher than CDF result
  - Less precise than exp.
- ➔ Progress on theory side welcome

B_c Lifetime

- B_c decay width has contributions from
  - Decay of b quark
  - Decay of c quark
  - Weak annihilation

➔ $\Gamma_{Bc} \approx \Gamma_b + \Gamma_c + \Gamma_W$



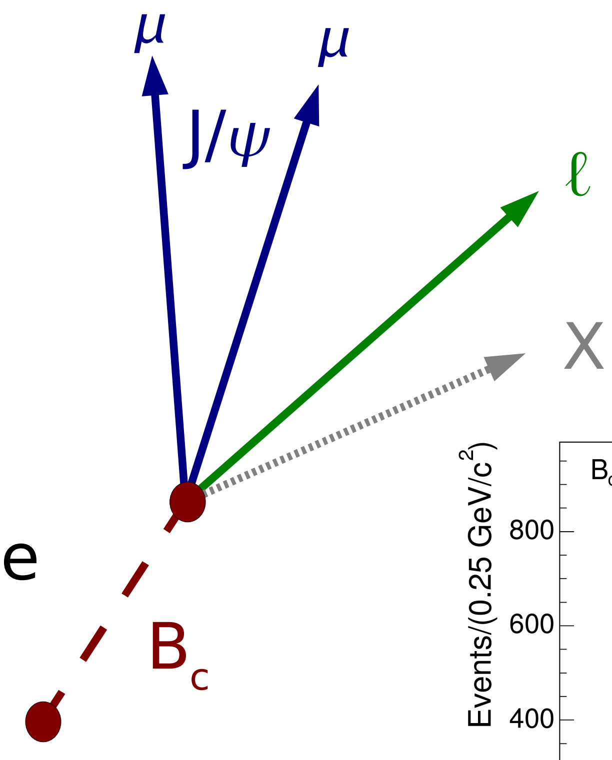
- Spectator model expectation:
  $\tau(B_c) < \tau(B^{0/+}) = 1.5$ ps
  $\tau(B_c) \lesssim \tau(D^{0/+}) = 0.4 / 1.0$ ps

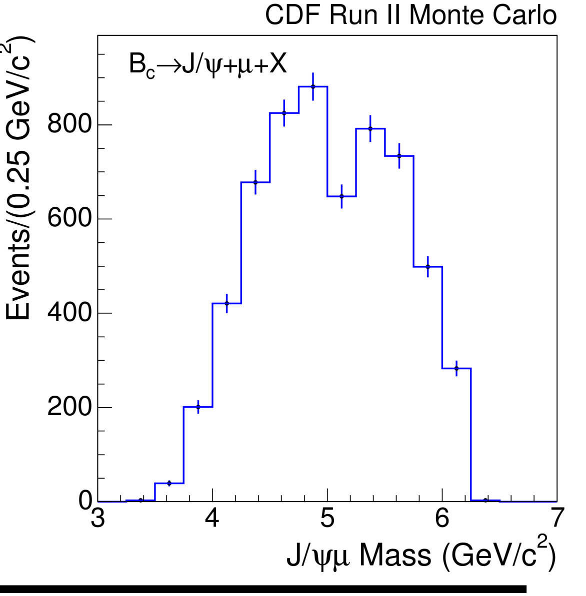
➔ Predictions: $\tau(B_c) = 0.4 – 0.6$ ps
[hep-ph/0308214 and references therein]

B_c Lifetime Measurement

Use inclusive decay $B_c \to J/\psi\ \ell\ X$, with ℓ = e or μ

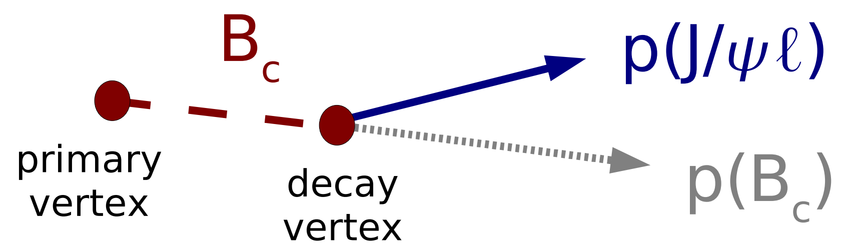
- ✔ trigger on $J/\psi \to \mu\mu$
  - ➔ no lifetime bias
- ✔ high statistics
- ✗ partial reconstruction
  - ➔ have to model missing momentum in decay time reconstruction
  - ➔ no narrow mass peak
- ➢ Understanding of backgrounds crucial





Decay Time Reconstruction

- $\mu\mu\ell$ vertex fit $\rightarrow$ decay length L

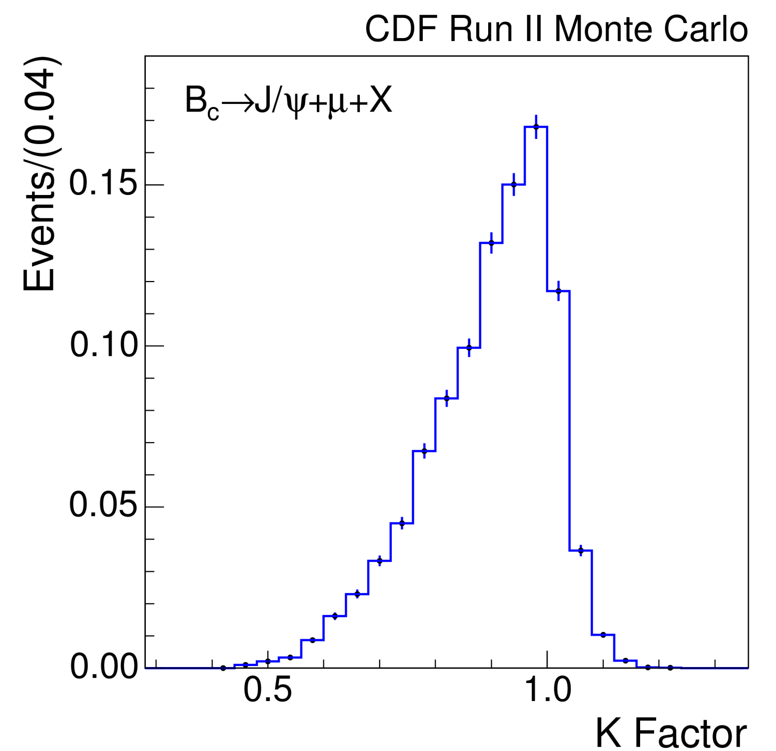


$$ct = \frac{L}{\beta\gamma} = \frac{L \cdot m(B_c)}{p(B_c)}$$

$$ct^* = \frac{L \cdot m(B_c)}{p(J/\psi\ell)} = ct \cdot \frac{p(B_c)}{p(J/\psi\ell)} = ct/K$$

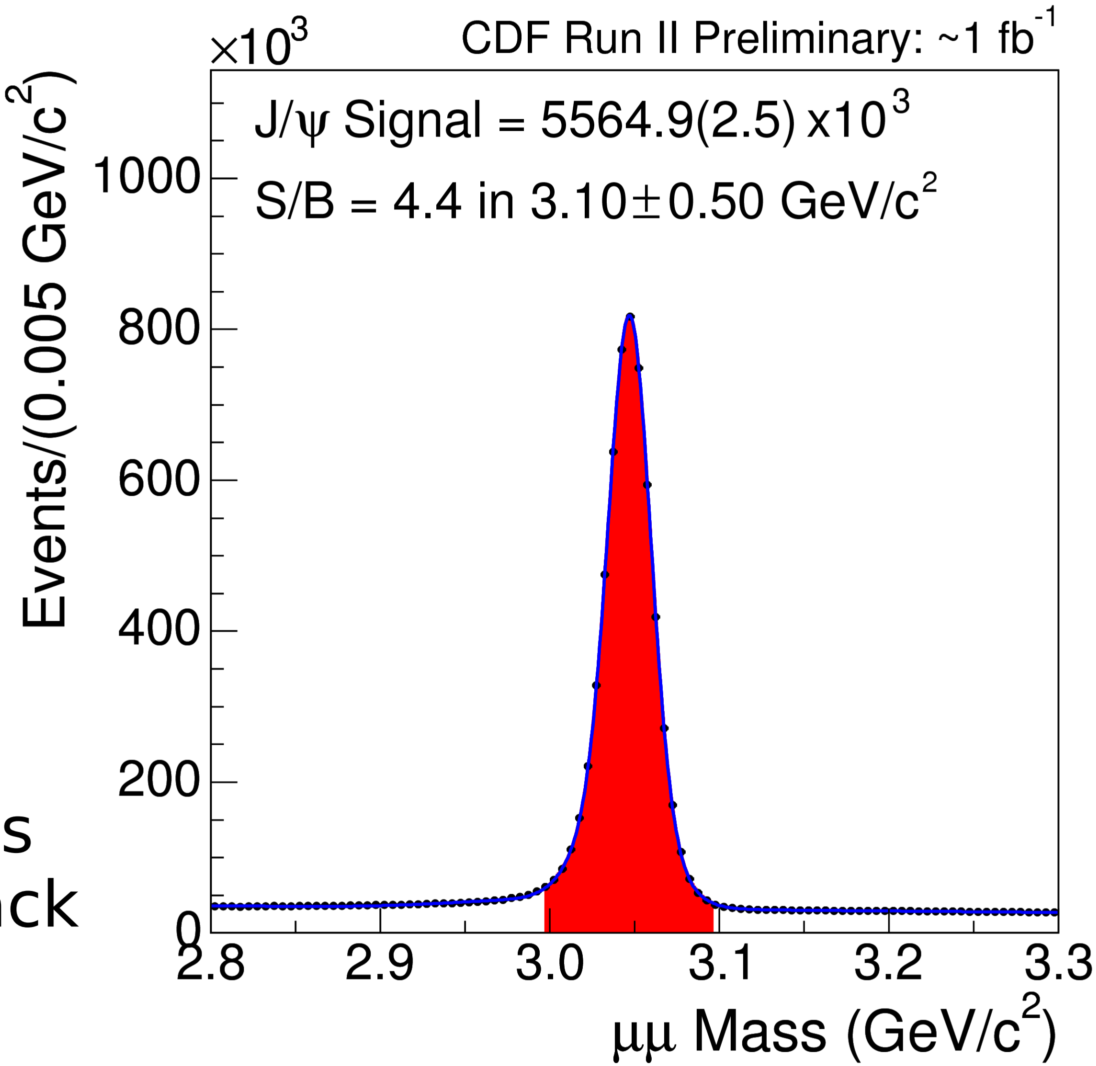
$$\Rightarrow f_{meas}(ct^*) = \exp(-Kct^*/c\tau) \otimes f(K) \otimes \mathrm{res}$$

- K-factor distribution from MC
  - Branching ratios (mainly $J/\psi\ell\nu$, O(1%) $J/\psi\tau\nu$ and $\psi(2S)\ell\nu$)
  - B_c momentum spectrum



Data Sample

- 1 fb^{-1}
- 5.5 million J/ψ
  - Muon selection: muon det., dE/dx
    - 572 $J/\psi\mu$ candidates
  - Electron selection: E_{em}, E_{had}, dE/dx
- Veto conversion electrons by identifying partner track
    - 1935 $J/\psi e$ candidates



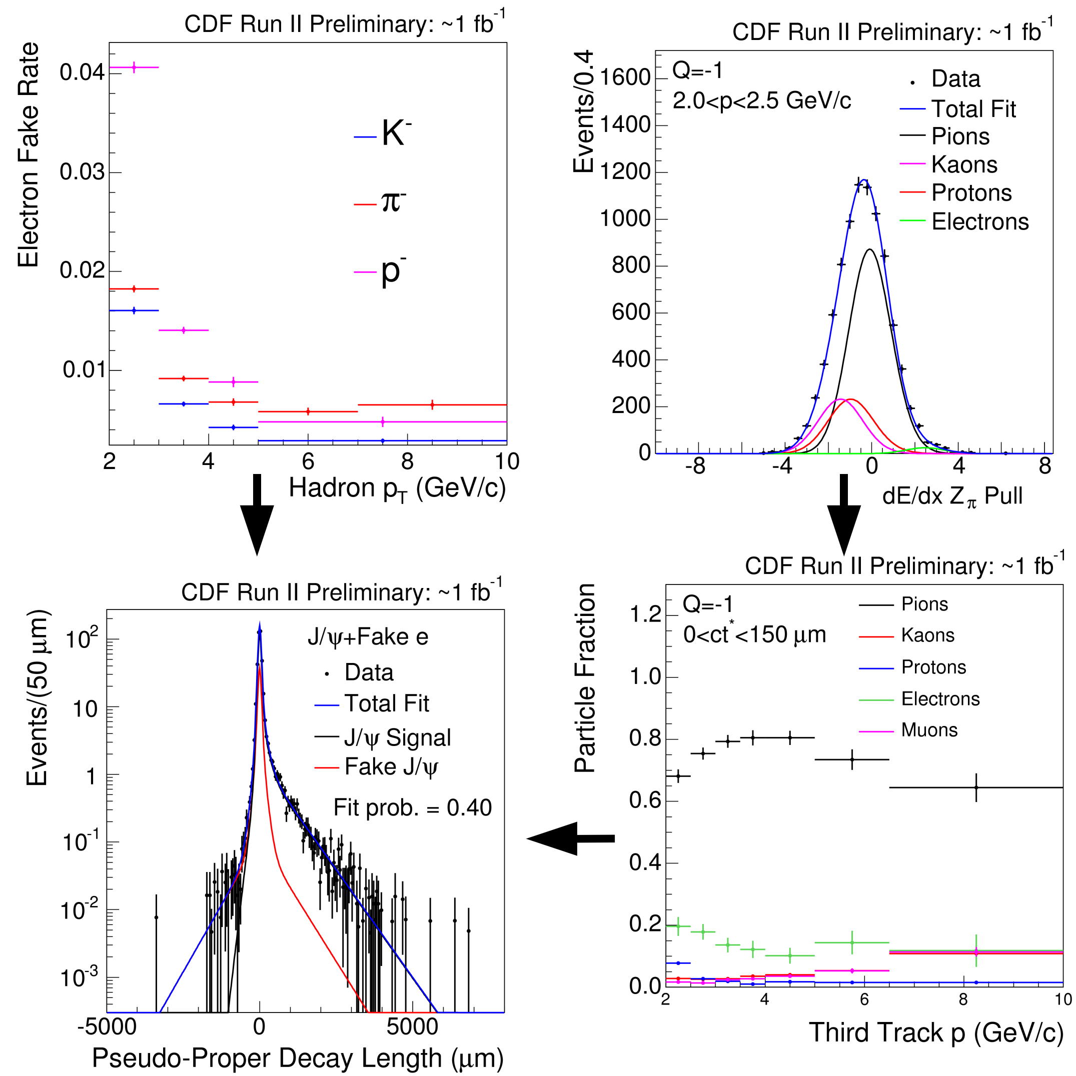
Backgrounds

- Fake J/ψ
  - → Estimated from J/ψ mass sidebands
- Prompt J/ψ from charm production plus lepton
  - → Prompt component in lifetime fit
- J/ψ plus hadron faking a lepton
  - μ: decay-in-flight or punch-through
  - e: hadron with electron like signature
- $b\bar{b}$ events with J/ψ from one and lepton from other b quark
- J/ψ plus conversion electron
  - → Estimated from conversion suppression efficiency

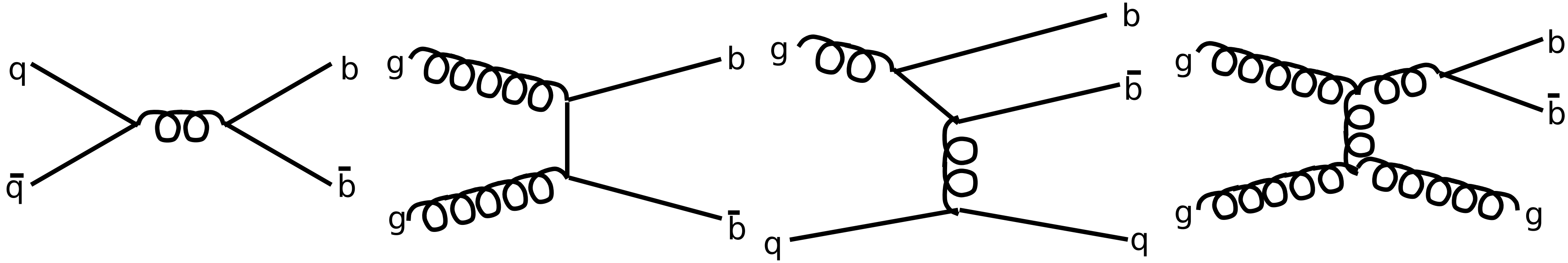
Fake Lepton Background

- Proton, kaon, pion fake probability measured from $\Lambda \rightarrow p\pi$ and $D^0 \rightarrow K\pi$ data
- Particle fractions determined from fit to dE/dx, ToF

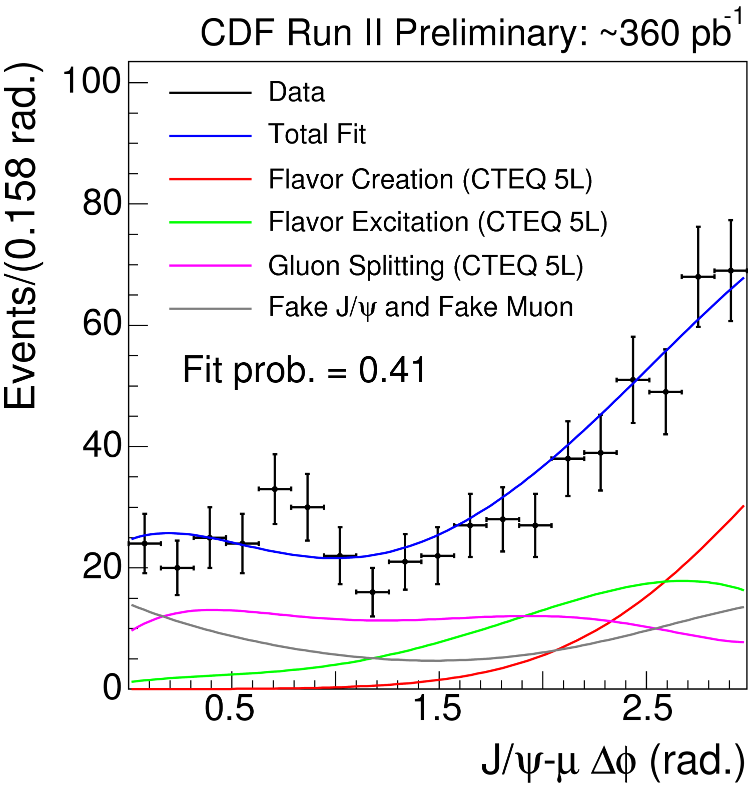
➔ Number of fake events and their ct^* distribution determined from J/ψ+track sample weighted with fake rate



$b\bar{b}$ Background



- Estimated from MC with production process fractions reweighted to match measured $\Delta\phi(J/\psi,\ell)$ distribution
- Normalized to $B^+ \rightarrow J/\psi K^+$



Lifetime Fit

- Background yields and ct* distributions
- Signal lifetime model

➔ Likelihood fit

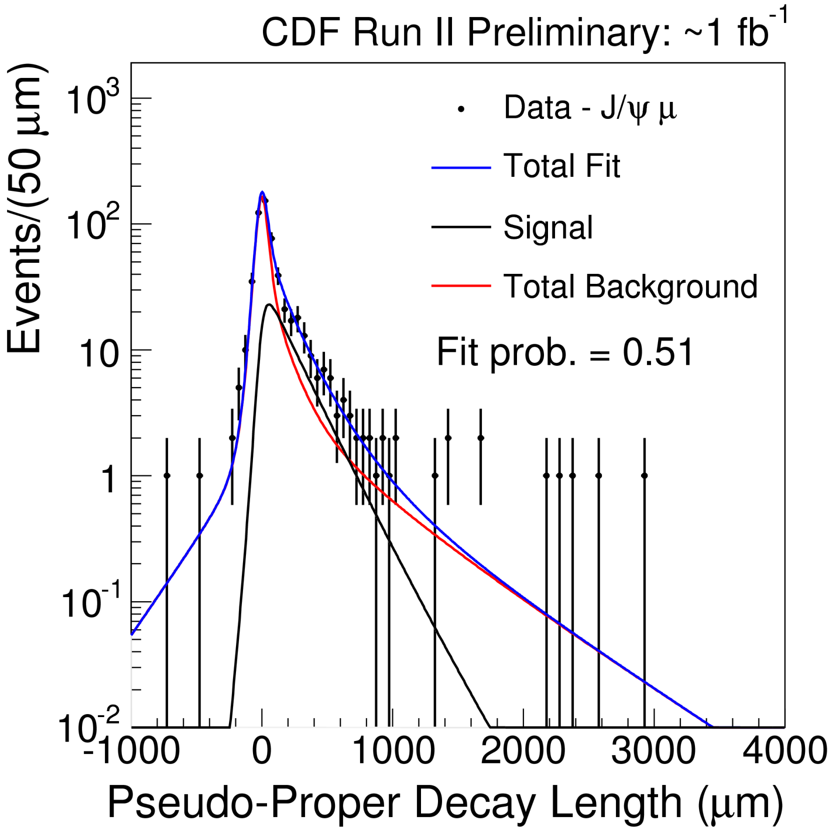
	$J/\psi\mu$	$J/\psi e$
Fake J/ψ	141.5 ± 8.4	315.2 ± 10.0
Prompt J/ψ	fit	fit
Fake lepton	96.1 ± 4.6	312.0 ± 4.1
bb	77.5 ± 7.9	222.5 ± 11.2
Conversions		416.8 ± 41.5

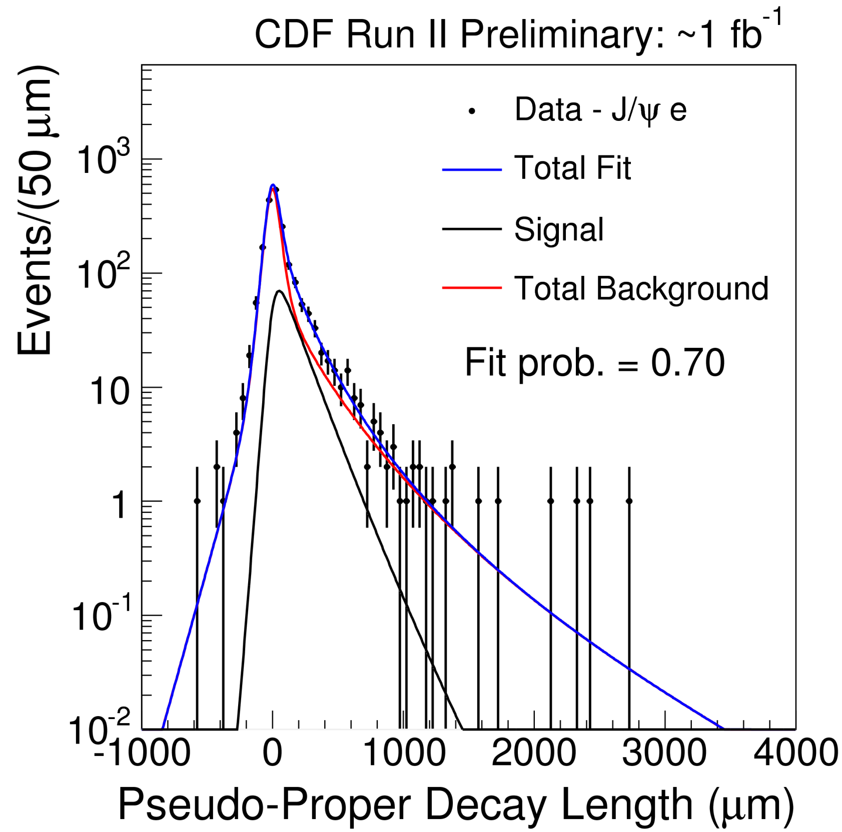
➢ Systematic uncertainties:

- Resolution function: 3.8 μm
- $b\bar{b}$ MC composition: 2.4 μm
- Silicon detector alignment: 2.0 μm
- Conversion estimate: 1.5 μm
- B_c momentum spectrum: 1.3 μm

➔ Total: 5.5 μm

B_c Lifetime Result



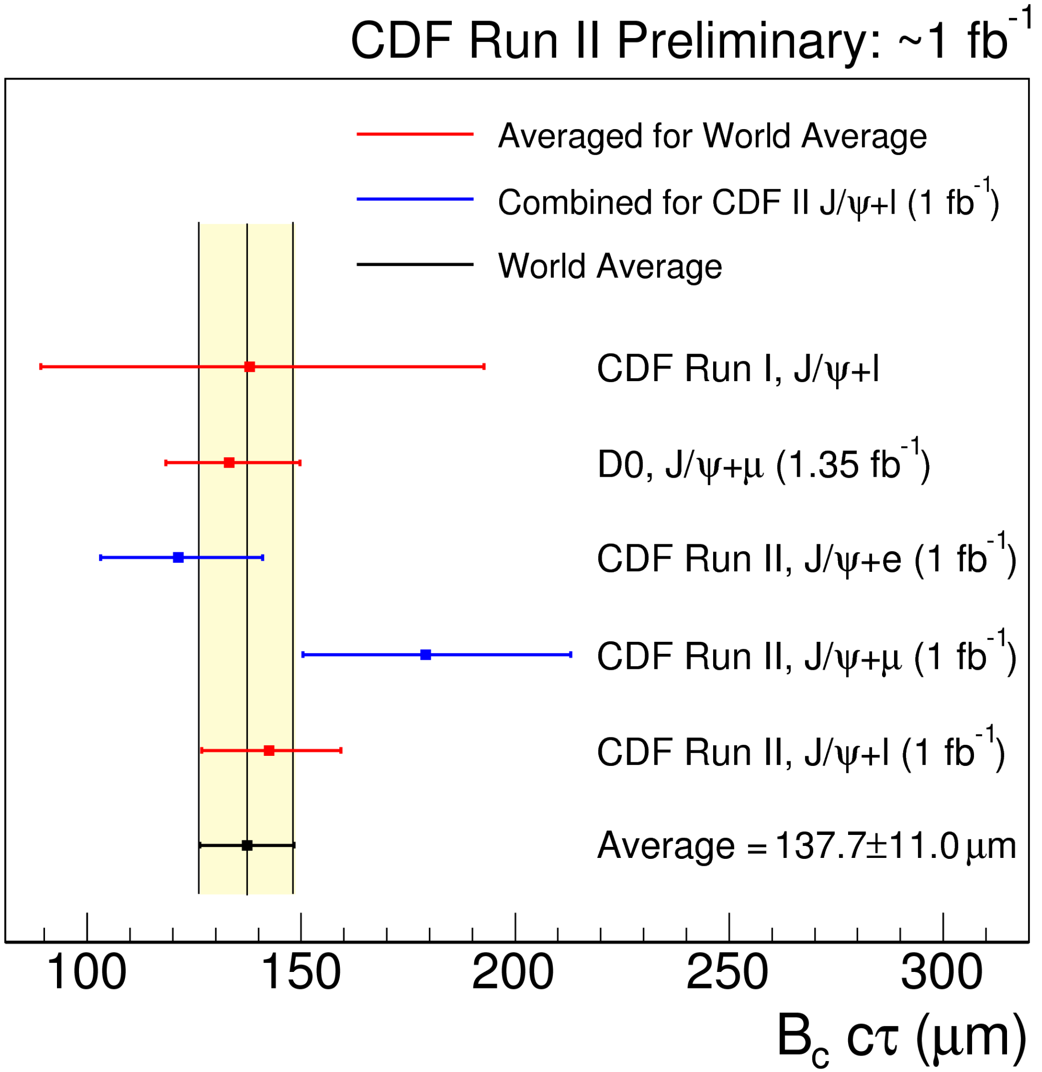


$c\tau_{\mu}(B_c) = 179.1\ ^{+32.6}_{-27.2}\ \text{(stat)}\ \mu\text{m}$ $\quad c\tau_{e}(B_c) = 121.7\ ^{+18.0}_{-16.3}\ \text{(stat)}\ \mu\text{m}$

→ Combined fit: $c\tau(B_c) = 142.5\ ^{+15.8}_{-14.8}\ \text{(stat)} \pm 5.5\ \text{(syst)}\ \mu\text{m}$

http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic

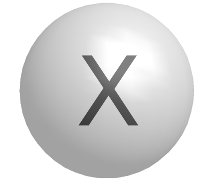
B_c Lifetime Summary



- CDF and D0 measurements agree well
- Lifetime of $\tau(B_c) = 0.475^{+0.053}_{-0.049}$ (stat) $\pm$ 0.018 (syst) ps within predicted range of 0.4-0.6 ps

→ Lifetime measurement in $J/\psi\pi$ mode in progress

X(3872)



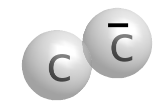
We know:

- Decays to $J/\psi\pi^+\pi^-$ (and $D^0\bar{D}^0\pi^0$)
- Mass ≈ 3872 MeV/c^2
- Narrow resonance
- $J^{PC} = 1^{++}$ or 2^{-+}
- Observed in B decays and prompt production in $p\bar{p}$

We don't know:

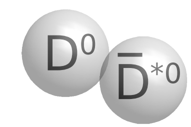
➢ **What is it?**

➢ Charmonium



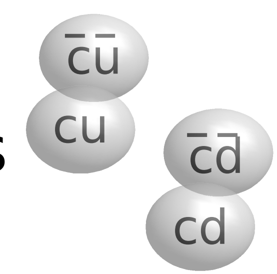
- ➔ Does not fit

➢ $D^0\bar{D}^{0*}$ molecule



- ➔ $m(X) \leq m(D^0) + m(D^{0*})$
- ➔ Mass measurement

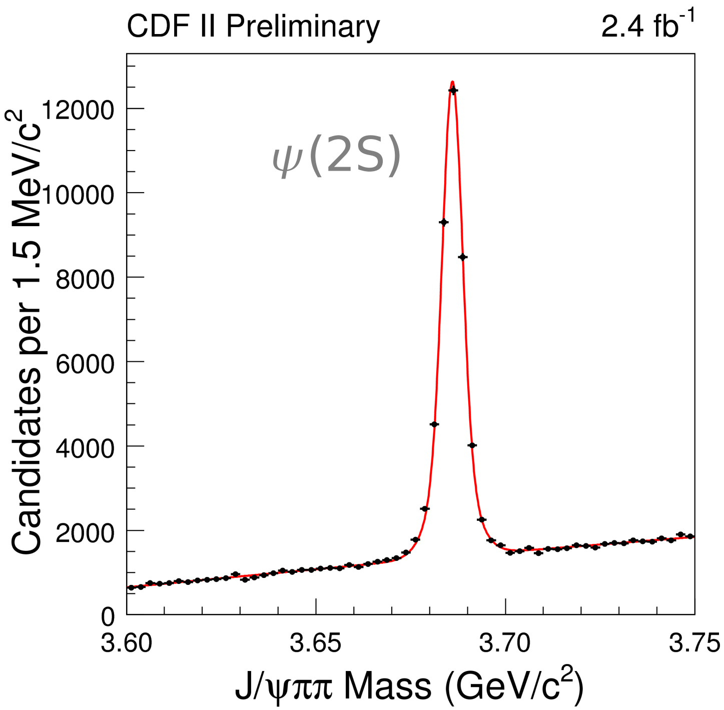
➢ 4-quark state

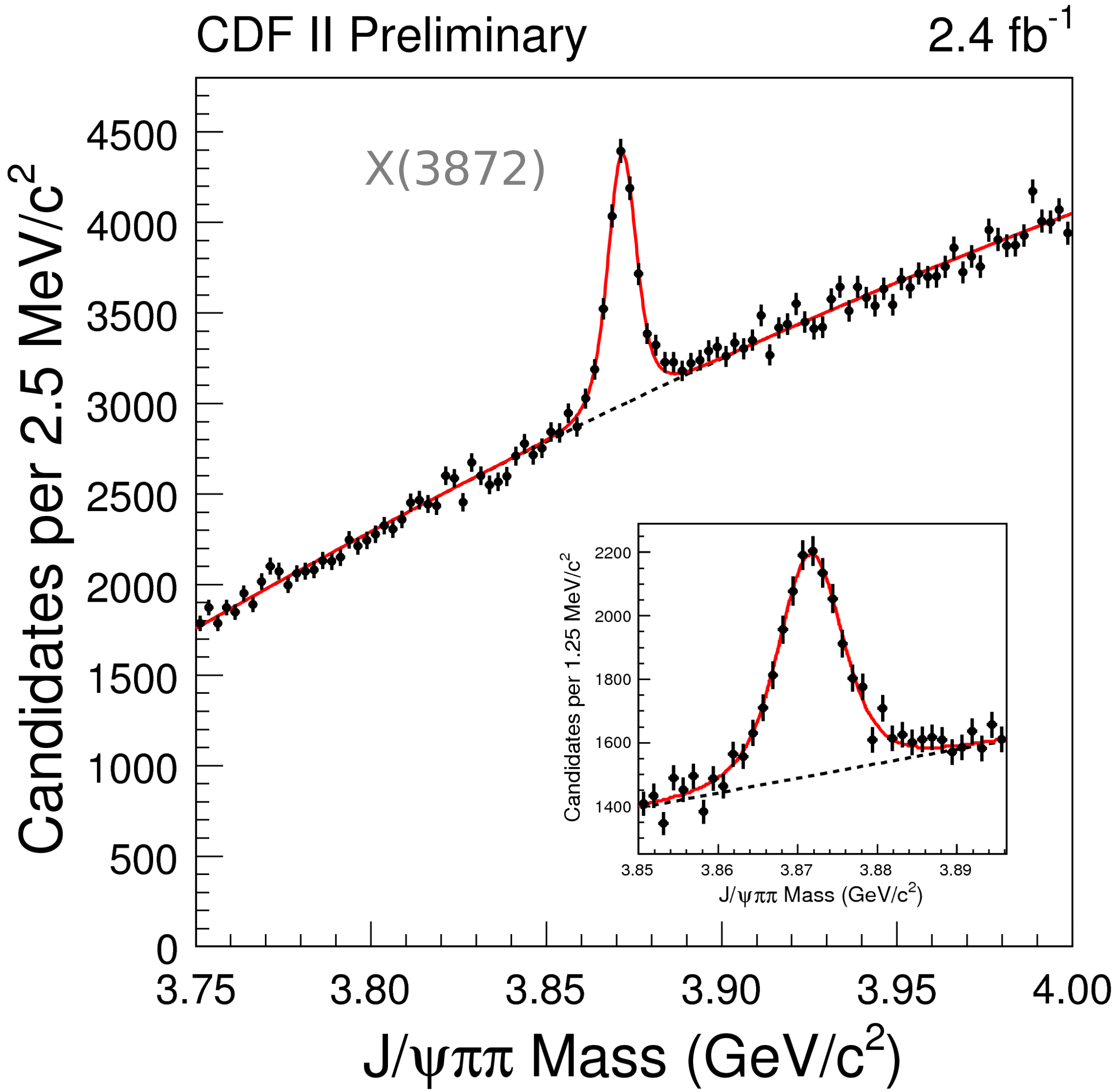


- ➔ Two neutral states
- ➔ Prediction [PRD71,014028 (2005)]: $\Delta m = 8 \pm 3$ MeV/c^2
- ➔ Check for two peaks

$J/\psi\pi^+\pi^-$ Data Sample

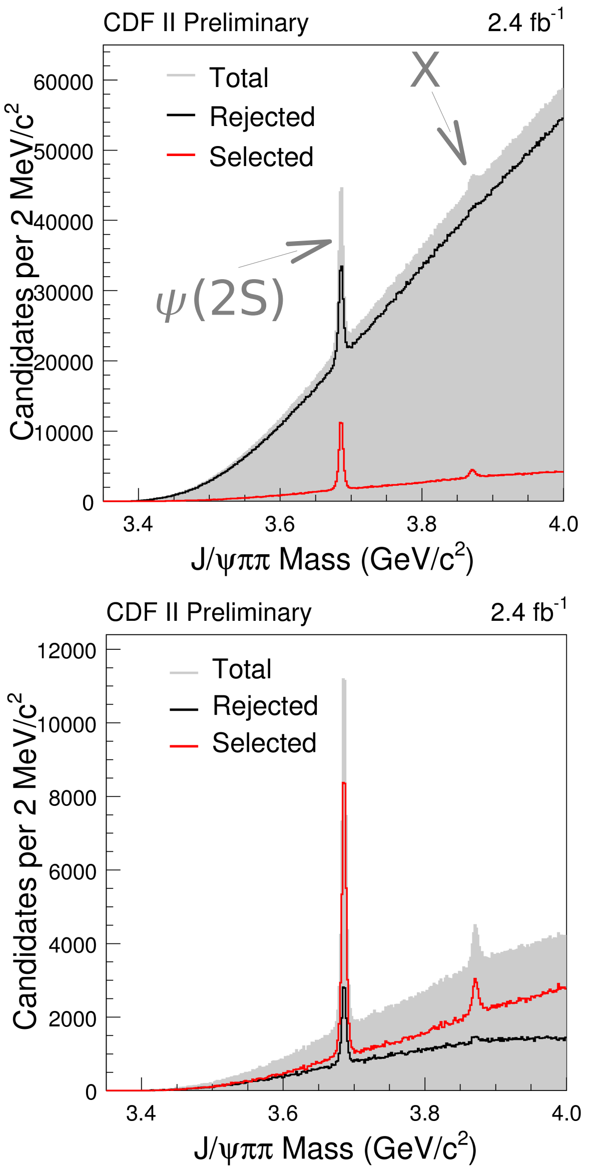
- 2.4 fb^{-1}
- Triggered by $J/\psi \to \mu\mu$
- Vertex fit with two further tracks





Selection

- Selection with neural network
  - Variables: Q, $p_T(\pi)$, χ^2, muon ID, ...
  - Background from sidebands, signal from MC
  - Check for bias with wrong-charge candidates
- Cut on number of candidates per event
- Selection optimized on significance $N_{MC} / \sqrt{N_{data}}$



Mass Shape Fit

Maximum likelihood fit

- Background: 2nd order polynomial
- Signal:
  - Non-relativistic Breit-Wigner
    - Γ = 1.34 ± 0.64 MeV
      (average of Belle/BaBar results in J/$\psi\pi\pi$ decay mode
      [PRL 91,262001; PRD 77,111101])
  - Resolution function
    - Sum of two Gaussians
    - Determined from MC

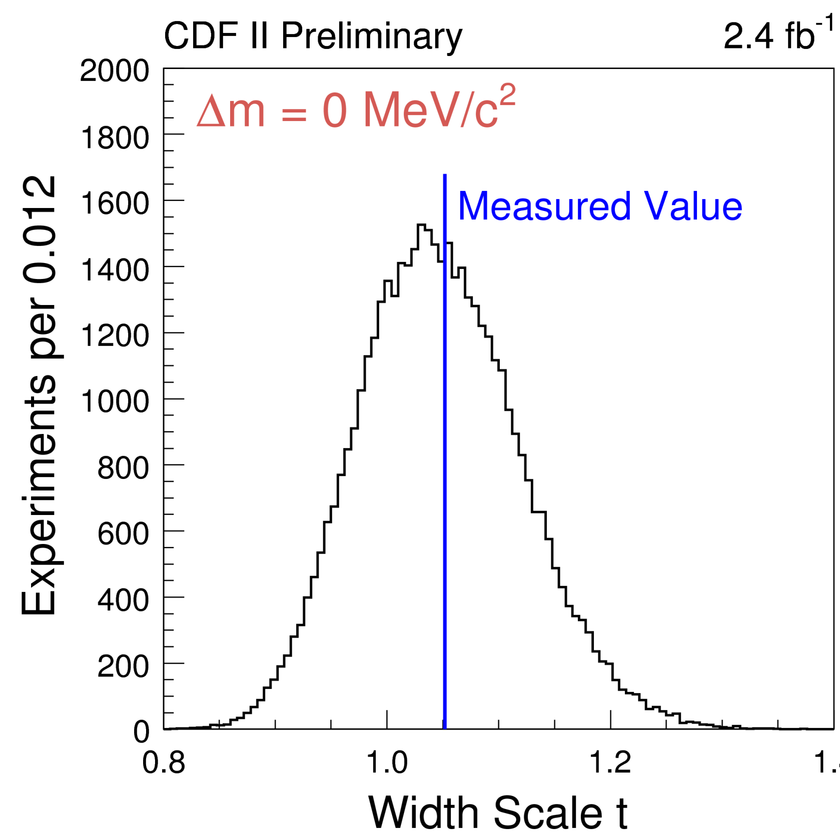
$$f_{meas}(m) = \mathrm{BW}(\Gamma) \otimes \mathrm{res}(\sigma_1, \sigma_2)$$

One-Peak Hypothesis Test

- Expect broader peak in case of two states
→ Scale width and resolution by fit parameter t

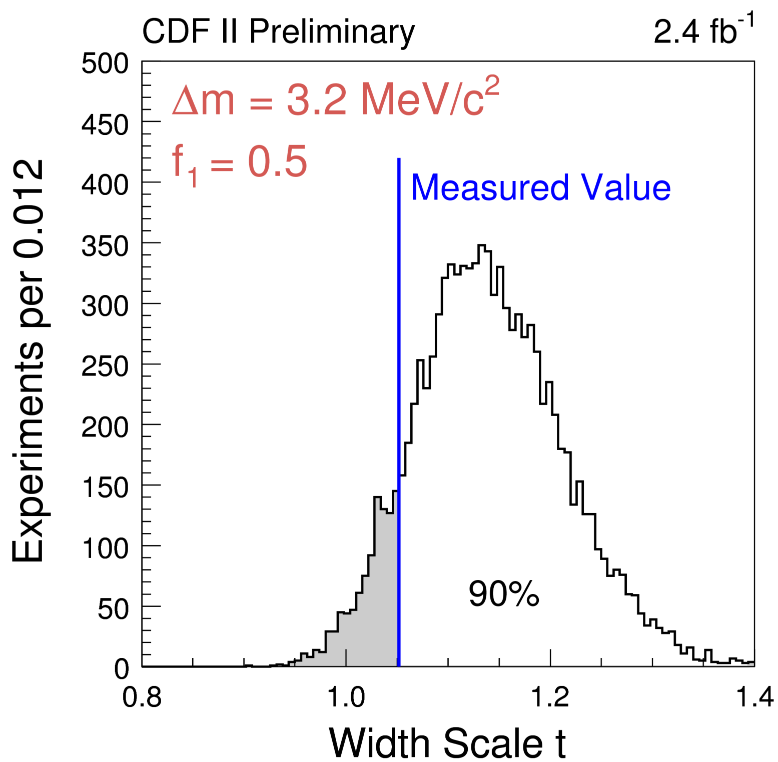
$$\Gamma \rightarrow t \cdot \Gamma \quad \sigma \rightarrow t \cdot \sigma$$

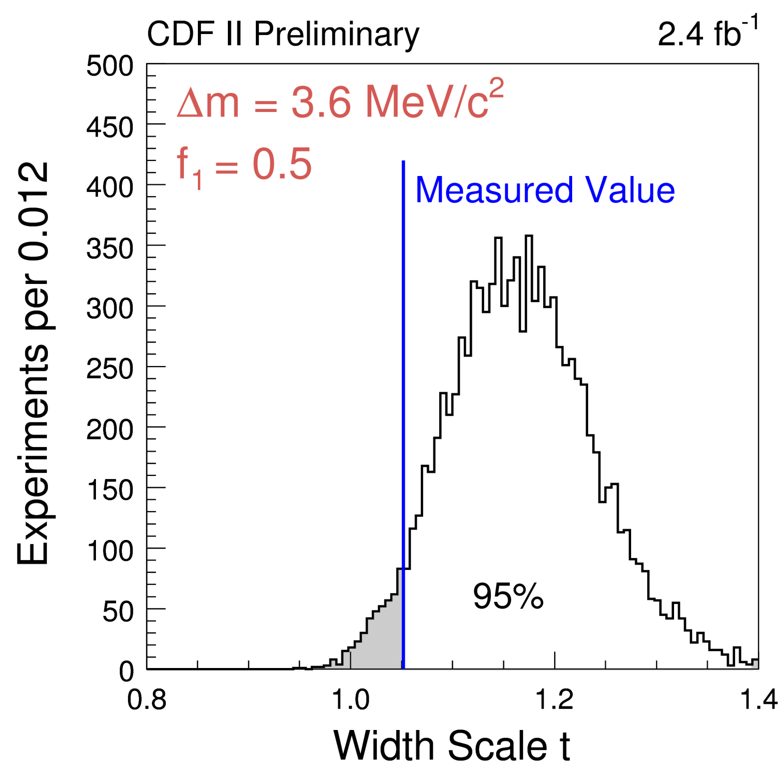
- Test statistics t:
  Is fitted value of t consistent with hypothesis of one peak?
- Generate pseudo experiments
- Take into account resolution correction by ~5% determined from $\psi(2S)$
- Answer: yes



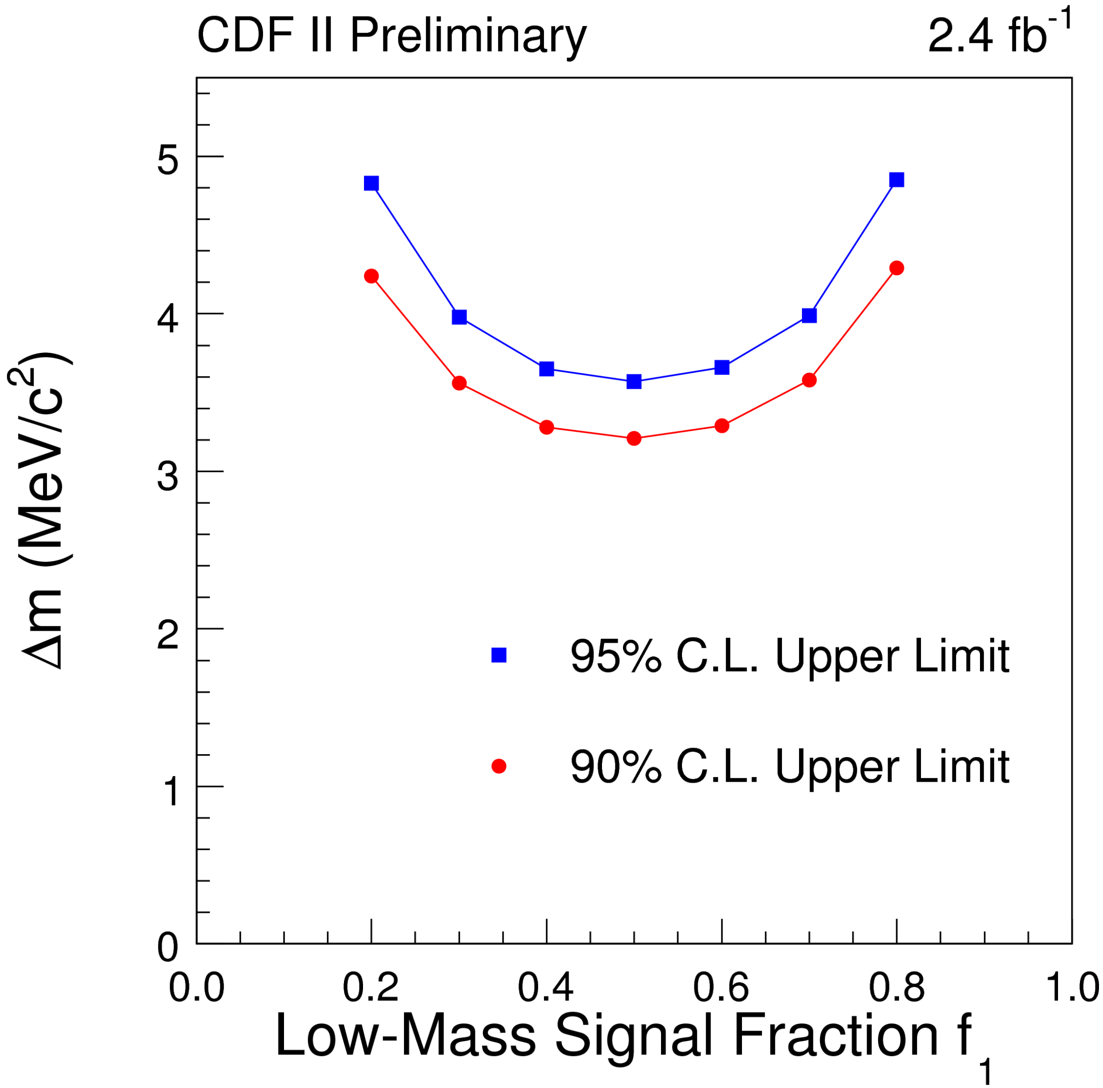
Two-Peak Hypothesis Test

- Is fitted value of t consistent with hypothesis of two peaks with mass difference Δm and light state fraction f_1?
- Generate pseudo experiments with two states (same shape)

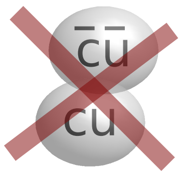




Limit on Mass Splitting



- For equal mixture of both states (f_1 = 0.5):
  - Δm < 3.2 MeV/c^2 at 90% C.L.
  - Δm < 3.6 MeV/c^2 at 95% C.L.
- Disfavors 4-quark model

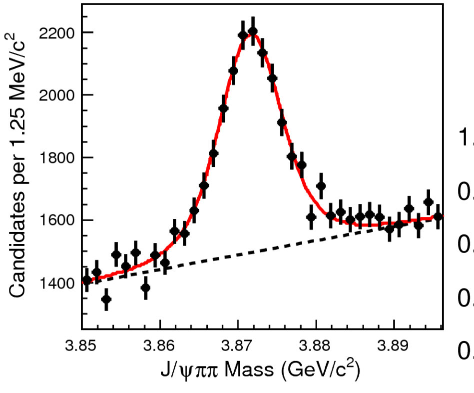


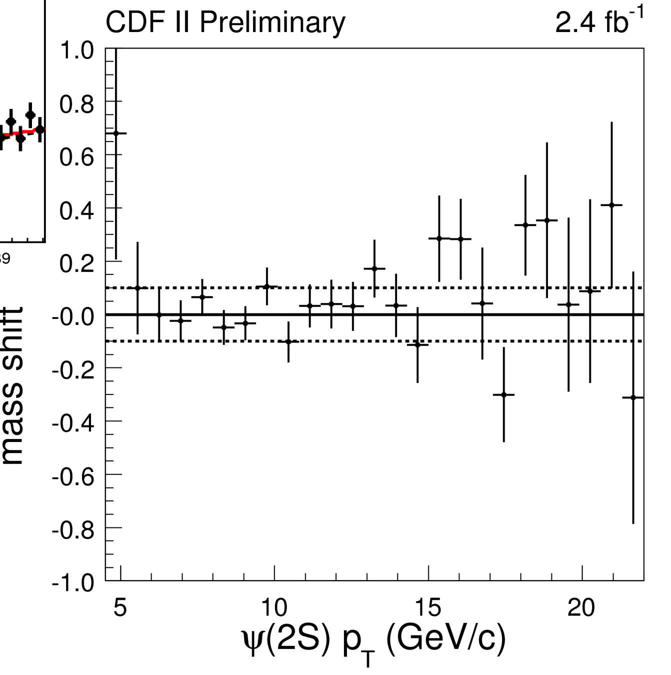
- Belle: $\delta m = m(X|B^+) - m(X|B^0)$ = $(0.18 \pm 0.89 \pm 0.26)$ MeV/c^2

http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-X-Mass

Mass Measurement

- Mass shape consistent with one peak → measure mass
- Unbinned likelihood fit



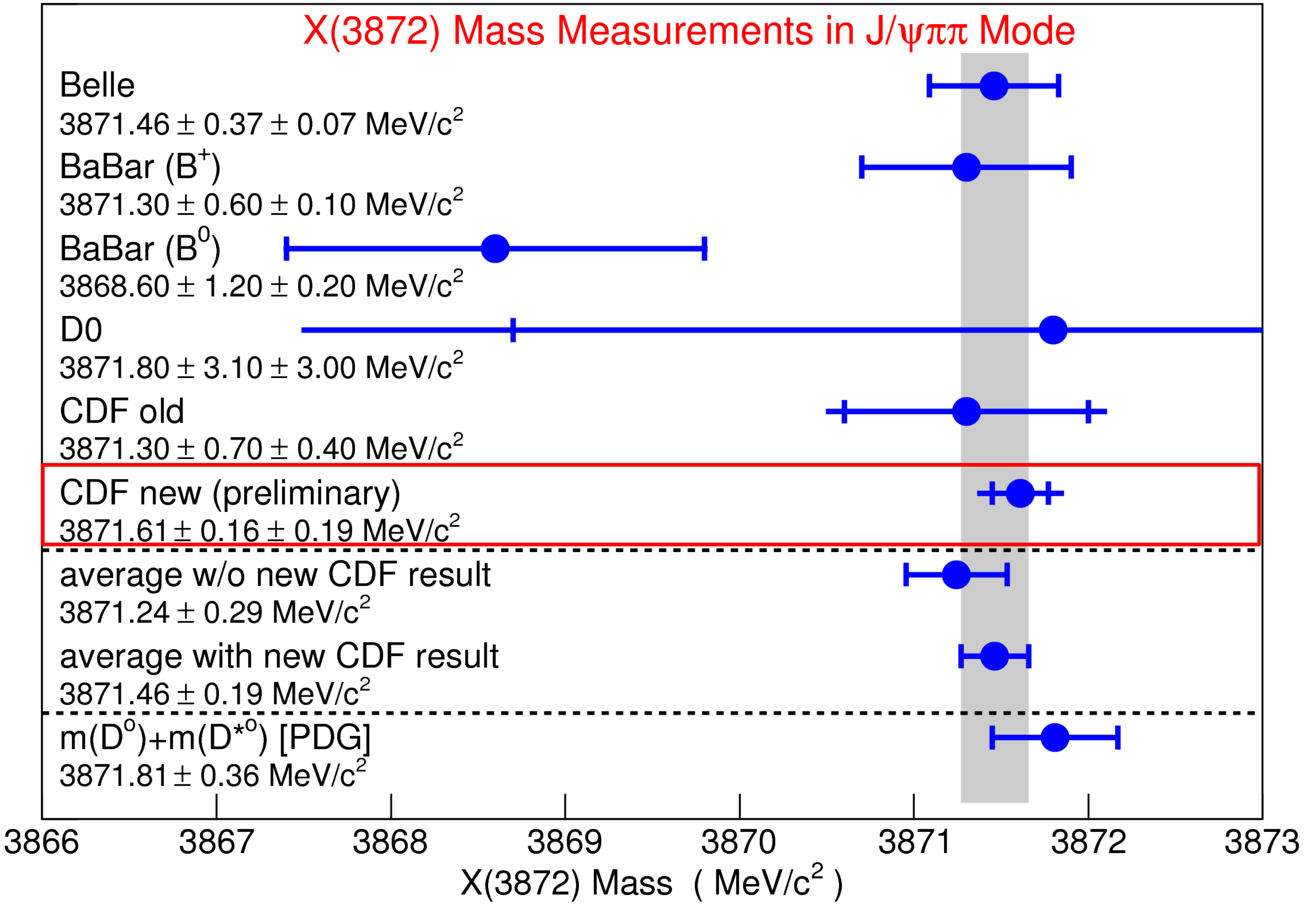


Systematic uncertainties:

- Fit model → negligible
- Momentum scale:
  - Check absolute scale on $\psi(2S)$:
    $m_{fit}(\psi(2S)) = 3686.03 \pm 0.02$ MeV/c^2
    $m_{PDG}(\psi(2S)) = 3686.09 \pm 0.04$ MeV/c^2
    → 60 keV
  - Dependence of $\psi(2S)$ mass on kinematic var. → 100 keV
  - ➔ Total (scaled by Q value) → 190 keV

X(3872) Mass Result

$m(X) = 3871.61 \pm 0.16\ (stat) \pm 0.19\ (syst)\ MeV/c^2$



http://www-cdf.fnal.gov/physics/new/bottom/080724.blessed-X-Mass

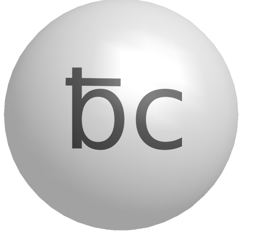
- Most precise measurement
- Consistent with previous results
- Improves precision of world average by factor ~1.5

➢ New average 0.35 MeV/c² (0.9σ) below DD* mass

D^0 $\bar{D}^{*0}$

Summary

B_c mass precisely measured

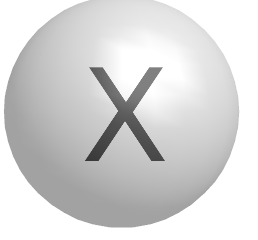


- Can theory catch up?

B_c lifetime measured in inclusive $J/\psi \ell X$ decays

- Precision of measurement and predictions at similar level
- Measurement in exclusive $J/\psi \pi$ mode in progress

Limit on X(3872) mass splitting determined



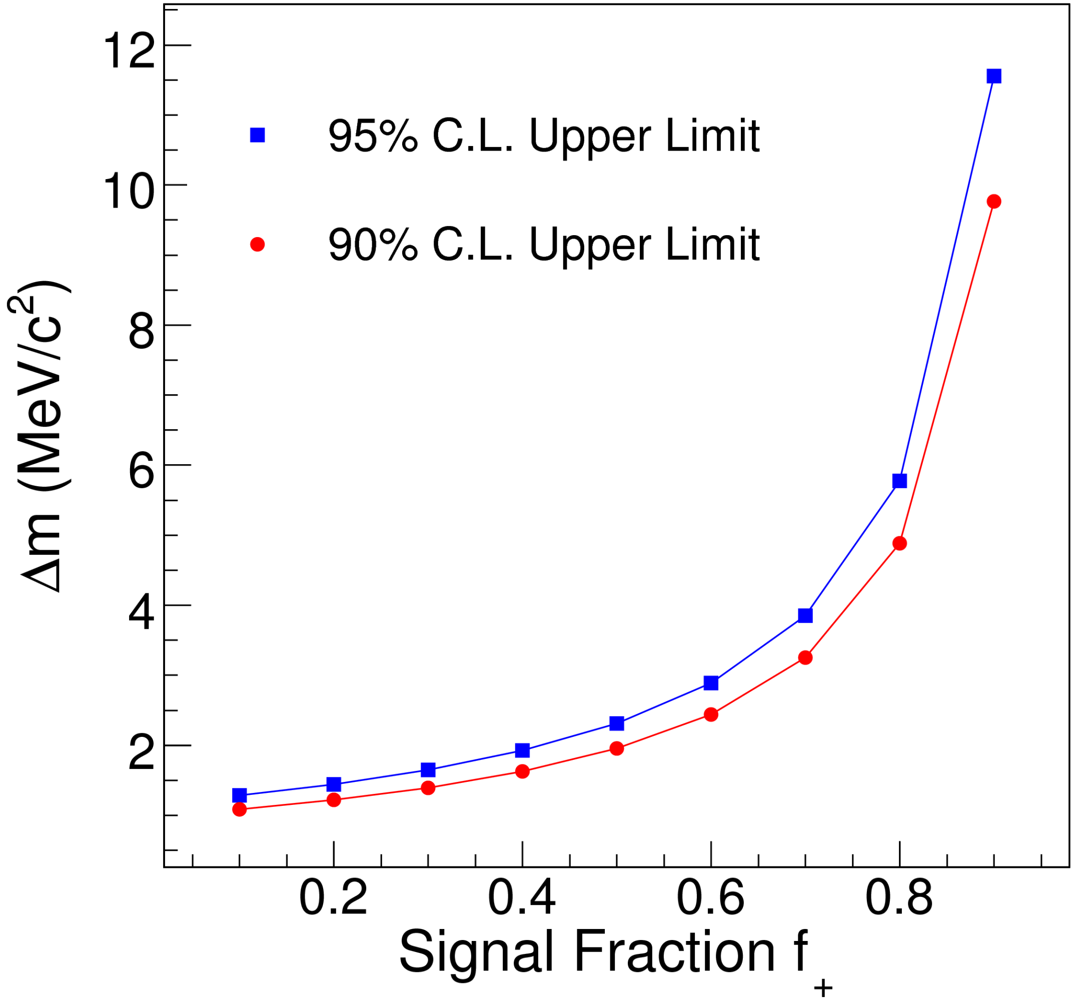
- 4-quark model disfavored

X(3872) mass precisely measured

- Need more precise DD^* mass for conclusion on molecule model
- What else?

Backup

X(3872) Mass Splitting Limit



- Assume mass of one of the states is measured by B-factories in B^+ decays
- Assume we measure average mass of mixture of two states

→ Limit on mass difference